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**An Assessment of New Applications for
Single-Crystal Piezoelectric Materials**

Lisa Veitch

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MEMORANDUM FOR DISTRIBUTION

FROM: Dr. Lisa C. Veitch

SUBJECT: An Assessment of New Applications for Single-Crystal Piezoelectric Materials

At the request of Dr. Wallace Smith, I am sending you a copy of "An Assessment of New Applications for Single-Crystal Piezoelectric Materials." A summary of this assessment was presented at the DARPA Piezocrystals Teaming Workshop: Piezoelectric Single Crystals for Electromechanical Transduction at the Hyatt Fair Lakes in Fairfax, VA on July 29-30, 1998. If you have any questions, please feel free to contact me at the address shown above. Thank you for your interest.

INSTITUTE FOR DEFENSE ANALYSES

IDA Document D-2151

**An Assessment of New Applications for
Single-Crystal Piezoelectric Materials**

Lisa Veitch

PREFACE

This work was performed under a Defense Advanced Research Projects Agency (DARPA) task entitled "Materials Science Analyses." The purpose of this task is to document the status of DARPA's Affordable Composites Program and to provide the necessary technical information and technical assessments for DARPA's Defense Sciences Offices (DSO) to make informed decisions on research and development (R&D) requirements and the direction of present and future R&D programs in materials science and materials processing.

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SUMMARY

Studies of single-crystal piezoelectrics began as early as the 1960s. Initial studies were limited to property measurements on very small crystals, and the data were questionable. In recent years, larger crystals (but still less than 1 inch in the largest dimension) have become available and enable more reliable property measurements. These property measurements indicate that the single-crystal materials have better piezoelectric properties than more conventional polycrystalline ceramics.

The purpose of this study was to determine the current commercial and military uses of piezoelectric materials, the properties that are important to these uses, and the impact of substituting single-crystal materials for conventional piezoelectric materials.

Development programs investigating the use of piezoceramic materials are ongoing in the following subject areas:

- Piezoelectric actuators
- Piezoelectric transducers
- Relaxor ferroelectric materials
- Piezoelectric ceramics
- Single-crystal piezoelectrics.

The possibility of restructuring these programs to take advantage of the properties of single-crystal piezoelectric materials was examined. It is the author's opinion, however, that until consistent single-crystal piezoelectric materials are produced, the existing piezoelectric programs should continue to focus on the more traditional materials in the original program plans. As better manufacturing techniques are developed and consistent data are obtained in the single-crystal piezoelectric programs, all piezoelectric programs should be re-evaluated to determine if single-crystal piezoelectric materials would have a greater impact than any of the other materials currently being developed. This evaluation would also have to consider the constraints in using these materials (e.g., size, availability on a large scale, power requirements, mechanical properties, and temperature dissipation).

Other areas of research that have been supported over the last 2 years were also examined and include:

- Phased array antennas that use thin-film ferroelectrics as phase shifters
- Two-dimensional (2-D) arrays that use ferroelectric materials for the bias-controlled transducers
- Vibration control, where either stacked piezoelectric actuators or piezoelectric fiber patches are used in aircraft, rotorcraft, satellites, and space structures
- Sonar where MicroElectroMechanical Systems (MEMS)-based devices incorporate PZT thin films in transducer devices
- Ferroelectric polymers for broadband detection of surface acoustic waves (SAWs)
- Non-destructive interrogation (NDI) on critical structural components using an impedance-based approach with a PZT wafer attached to an area of interest
- Micropumps that use PZT thin films for actuation
- Microwave and infrared (IR) detectors that use ferroelectric thin films with MEMS devices
- Next-generation telescopes that use stacked ferroelectric actuators to increase focusing capability.

This study also included a workshop to which representatives from all the Services and the National Space and Aeronautics Administration (NASA) were invited to participate at the Institute for Defense Analyses (IDA) on April 29, 1998. The purpose of this workshop was to explore completely new uses of piezoelectric materials. The results of the IDA workshop were categorized into six areas: power conversion, sensors, optics, actuators, human factors, and systems. Table S-1 lists these areas and the applications in which the participants of the IDA workshop believed single-crystal piezoelectric materials would have the greatest impact.

The workshop participants developed a list of single-crystal piezoelectric issues that focused on what was needed to use single crystals in the applications identified in the workshop:

- Manufacturability: size, orientation, quantity, other forms (such as single-crystal fibers)
- Quality standards to yield consistent material
- Uniform aging characteristics

Table S-1. Novel Military Uses for Single-Crystal Piezoelectric Materials

Area	Applications
Power conversion	Boat hull skins that generate electric power on boats Person power converted to electrical power Power projectiles Wing motion converted to electrical power Wave motion converted to electrical power Power recovery from mechanical devices (vibration, friction, and thermal) Micro-strip antenna Electric cars
Sensors	Structural health monitoring sensors that are built into material and give larger signals than current non-destructive evaluation (NDE) sensors Microphones for sensing shock waves Load sensors Mast-mounted sight for micropositioning
Optics	Deformable mirrors Electro-optical acoustic applications to control jitter Gun sights
Actuators	Micropositioning gun barrels or telescopes Biomechanical enhancement for insects (e.g., insect wings assisted with actuators) Fine adjustment at tool heads Projectile control Ejector actuator for munitions Micropumps for vacuum systems Propless propulsion Active propeller and turbine blades Variable compliance gun stock Flutter detection in wing tunnel tests Wing twist/rotary twist Internal actuation within a structure Active air foil damping RF MEMS devices where piezoelectric films are used for actuation Controlling kinetic energy projectiles by changing the shock wave Microminaturization revisited
Human factors	Inflatable inner soles of shoes Micro-pumps (self-contained air conditioner) Lumbar seat control (back support that conforms to different conditions) Breathing fabric "Superman suit"
Systems	Modified beam rider Shape-change antenna Mini high-cycle fatigue machines Acoustic refrigerators Shear rate monitoring in molding process Noise and vibration reduction systems in machinery Micro-unmanned aerial vehicles (MAVs) Shark skins for variable geometry Turbine engine inlets Active control in weapon systems Localized ultrasonic energy source in composite processing

- Electrical and mechanical biasing
- Stackability
- Linear performance in temperature ranges for military usage
- Coupled/dynamic modes
- Hazardous waste concerns
- Sensitivity to other materials
- Internal power dissipation (must be efficient)
- High-temperature capability/sensitivity
- Parallel crystal growth with silicon and sapphire for devices
- Weight
- Built-in pre-stress for crystals
- Cost (in comparison to conventional ceramics)
- Cutting of crystals
- Existent suppliers.

The workshop participants determined that the two most important issues for the single-crystal materials were manufacturability (size, orientation, and so forth) and quality standards that would yield consistent materials.

I. INTRODUCTION

Throughout the literature, the author has come across several terms related to piezoelectricity. These terms have been interchanged and sometimes used in the wrong sense when describing a certain piezoelectric behavior.

This introduction reviews the fundamentals of piezoelectricity and provides a demarcation in nomenclature that will be used in the remainder of this document.

A. FUNDAMENTALS OF PIEZOELECTRICITY

Piezoelectricity is the ability of certain crystalline materials to produce an electrical charge proportional to an applied mechanical stress. The converse piezoelectric effect, where mechanical strain is proportional to the applied electric field, is also true. Of the 32 crystal classes, 21 are noncentrosymmetric. Twenty of the noncentrosymmetric classes are piezoelectric, and, within these 20 classes, 10 are polar (i.e., these materials have a dipole moment). The 10 polar crystal types are pyroelectric as well as piezoelectric because of their polarization behavior. In a pyroelectric crystal, a change in temperature produces a change in the magnitude of the dipole.

Ferroelectrics are unique pyroelectrics—an electric field or a mechanical stress can change the direction of spontaneous polarization. These additional features of pyroelectric materials cannot be predicted. They are determined experimentally. Other properties common to ferroelectric materials are large dielectric permittivities and large piezoelectric coefficients. Ferroelectrics exhibit a hysteresis loop for polarization vs. electric field plots below the Curie or phase-transition temperature (see Figure I-1). The hysteresis implies the existence of domains (i.e., regions within which electric dipoles are parallel to one another and in the same direction). Above the Curie temperature, dipoles do not exist, and the material is paraelectric (Ref. 1).

The features of the hysteresis loop can be understood as follows: the sample is cycled at a field strength that is high enough to give saturation (indicated by the slope intercepts of the hysteresis to the P axis in Figure I-1). At the highest electric fields, all domains have been switched into the field direction so that an increase of the field is only

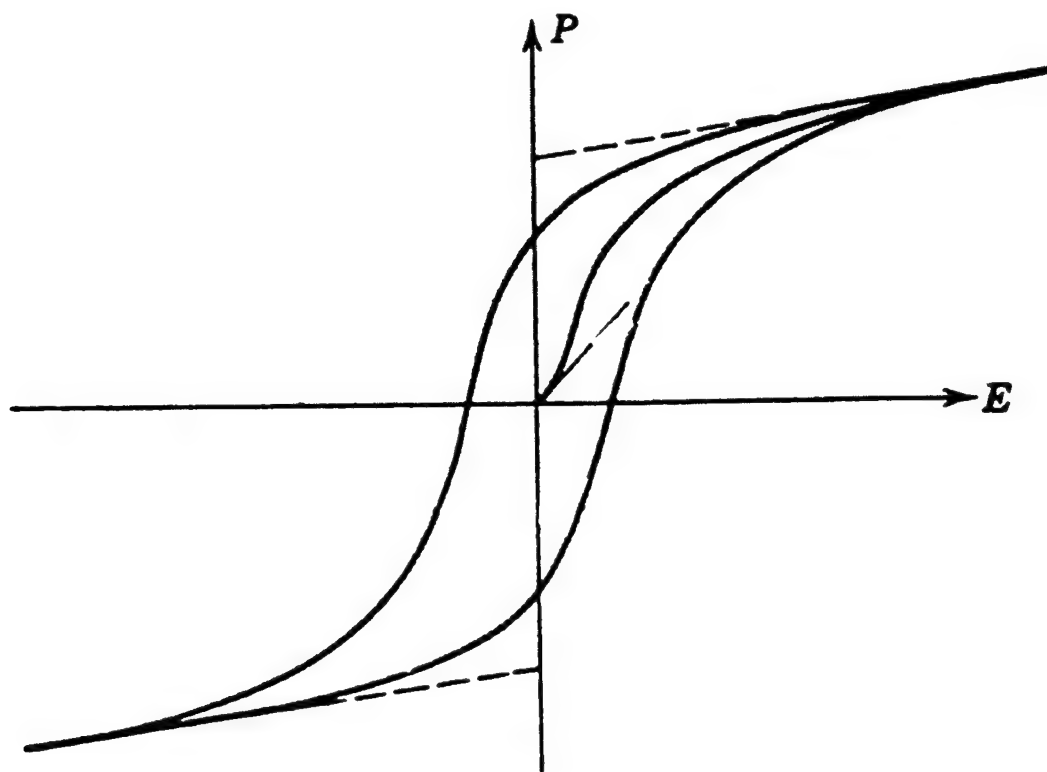


Figure I-1. Hysteresis for Ferroelectric Materials

Note for Figure I-1: The P axis (Polarization) is expressed in Coulombs/ m^2 . The E axis (Electric Field) is expressed in V/cm.

able to increase the polarization within domains. When the field is reversed, some domains retain their former alignment so that the specimen has a remnant polarization at zero field. A field in the reverse direction of sufficient magnitude (the coercive field) is needed to reverse the domains fully.

The perovskite group of ferroelectrics—the most important crystal group for these kinds of materials—shows the structural significance of dipole reversal. The best known member is Barium Titanate ($BaTiO_3$), which is cubic above the Curie temperature and tetragonal below the Curie temperature. For cubic $BaTiO_3$, titanium ions are in the center of the oxygen octahedras (see Figure I-2). While titanium is centrally situated in the cubic form, it is off-center in the tetragonal form. The displacement of the oxygen's center of gravity against titanium is the main reason for the reversible dipole moment of a unit cell of $BaTiO_3$. Figure I-3 shows the dielectric constant vs. temperature of pure $BaTiO_3$ and the three distinct phase transitions that take place in $BaTiO_3$ over the given temperature range.

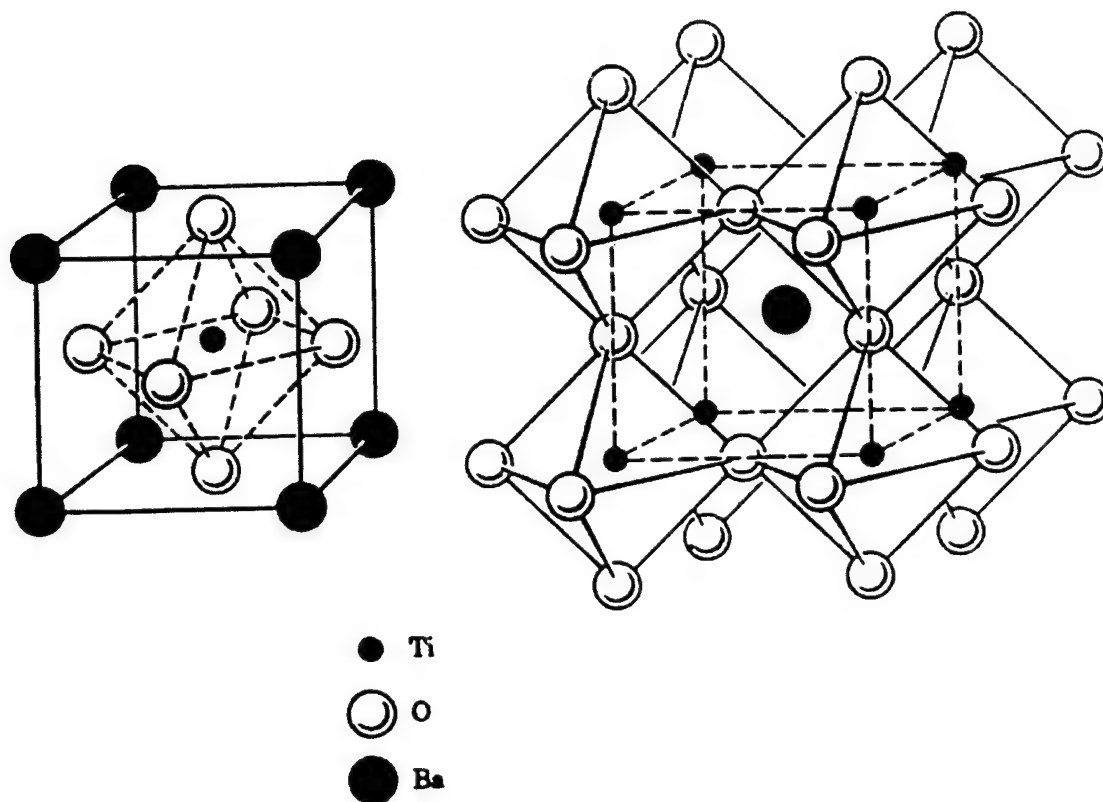


Figure I-2. Perovskite Crystal Structure

The highest dielectric constant occurs at 130 °C, the Curie temperature (Refs. 1-3). The Curie temperature can either be increased or decreased by substituting impurities, such as Sr^{+2} or Cd^{+2} for Ba^{+2} , or by substituting Zr^{+4} for Ti^{+4} .

Relaxor ferroelectrics are characterized by a strong dispersion of the dielectric permittivity, with frequency and the absence of macroscopic polarization even at temperatures much below the temperature of the maximum dielectric constant. A statistical inhomogeneity in the distribution of the B_1 and B_2 cations in the B sites of the $\text{A}(\text{B}_1\text{B}_2)\text{O}_3$ perovskite crystal structure explains this unusual dielectric response of relaxor ferroelectrics. This chemical disorder is responsible for the formation of microregions within the material, and these microregions have widely different Curie temperatures. In other words, relaxor ferroelectrics do not have a well-defined Curie temperature; rather, they exhibit a Curie temperature range over which the material is a statistical mixture of paraelectric and ferroelectric regions. As the temperature decreases from the high-temperature paraelectric state, the microregions gradually coalesce into macrodomains, which gives rise to a diffuse

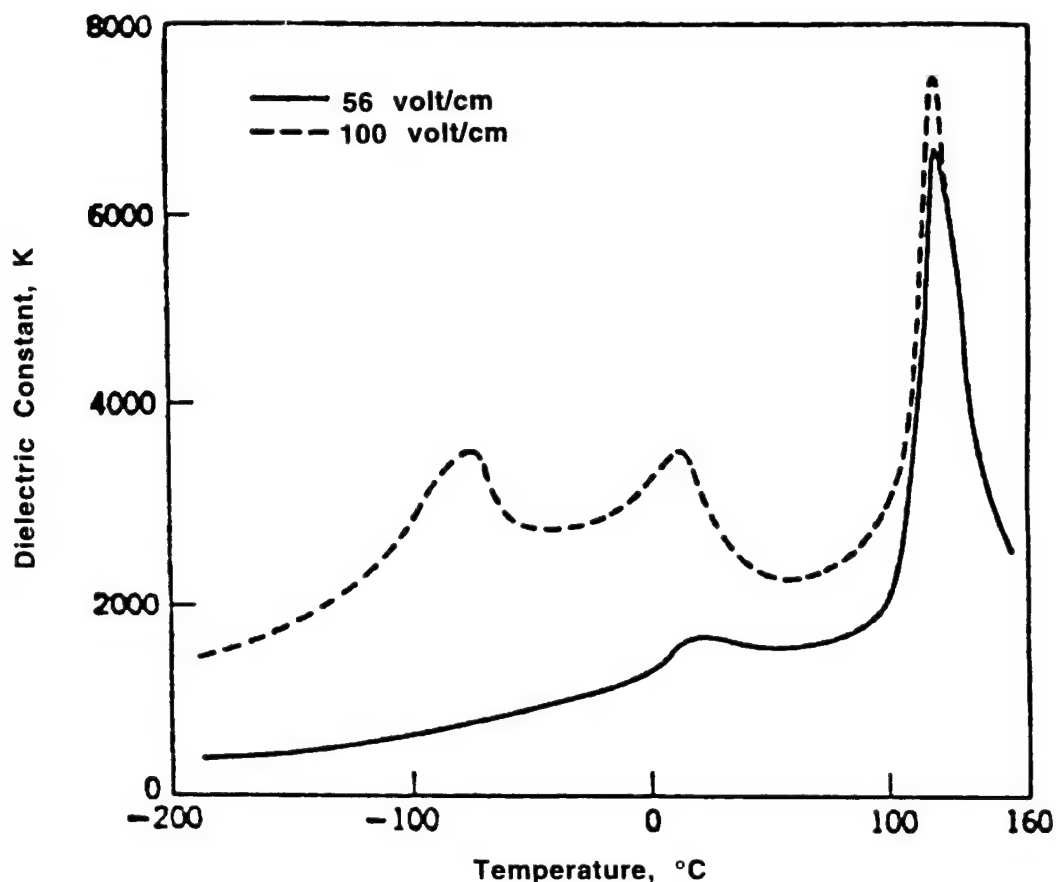


Figure I-3. Dielectric Constant vs. Temperature for BaTiO₃ at Different Field Strengths

phase transformation. The polarization fluctuations associated with the polar microregions are dependent on the electric bias field and measurement frequency. The dielectric constant drops off rapidly with frequency (hence, the name “relaxor”) because it takes time for the polarization fluctuations to respond. Direct current (DC) bias fields favor macrodomain coalescence—having the same effect as lowering the temperature. This classical interpretation of the relaxor behavior, however, is not completely successful in explaining all the complex properties of relaxor ferroelectrics (Refs. 2,3).

B. MATERIAL PROPERTIES

Most of the piezoelectric and ferroelectric materials are polycrystalline ceramics. Research and development (R&D) has also been conducted in piezoelectric polymers and single-crystal relaxor-based ferroelectrics.

Table I-1 compares some of the main material properties of 9 different piezoelectric ceramics and single crystals. In Table I-1, the materials PZT4 and PZT5H refer to "soft" and "hard" piezoceramics, respectfully. In a "soft" PZT, the domain walls are not pinned, and the motion of the domain walls contributes to the size of the dielectric and piezoelectric coefficients. In a "hard" PZT, the domain walls are pinned and are not as mobile as the "soft" PZT domains. The material parameters are tensor quantities and are related to the symmetry of the crystalline system. The numerical subscripts of these quantities refer to the matrix notation of these quantities. The numbers in parentheses under the single-crystal piezoelectrics [lead zinc niobate (PZN), lead zinc niobate/lead titanate (PZN/PT), and lead magnesium niobate/lead titanate (PMN/PT)] are the crystallographic directions in which the material properties were measured.

Only in the last 2 years have single-crystal piezoelectrics been reported to have high electromechanical coupling and high strain levels compared to conventional polycrystalline ceramics (Refs. 5-7). These properties are of particular importance for actuators requiring high strain and low hysteresis at a given electric field. Important material properties for transducers include high electromechanical coupling, a wide range of dielectric constants, and low losses. Single crystals could enhance device performance and eventually replace some of the current piezoelectric and ferroelectric materials. Because of these enhanced properties, single crystals could also be used in ways that were not previously possible with polycrystalline piezoelectrics.

As evidenced in Table I-1, however, several parameters are missing for the single-crystal piezoelectrics. Calculating most of the missing properties is possible, provided that the necessary parameters are available. For example, the elastic compliance tensor, s_{11}^E , can be calculated from the equation $k_{31} = d_{31}/(s_{11}^E \epsilon_{33}^T)^{1/2}$; however, according to Table I-1, not enough known properties exist to determine s_{11}^E . Other equations could be used to determine s_{11}^E , but a similar situation would be apparent because of the lack of available data. Work has begun to address these missing electrical properties (Ref. 8). Some work has also started to investigate cycles to failure under electrical and mechanical loads. Preliminary mechanical property data suggest that the single-crystal piezoelectric materials are much weaker than conventional polycrystalline piezoelectrics (Ref. 9). Until more data are available, exploiting the single-crystal piezoelectric materials fully (with confidence in existing or new devices) will be difficult for designers.

Table I-1. Major Properties for Piezoelectric Materials
(Source: References 4 and 5)

Material Parameter	Piezoelectric Ceramics						Single-Crystal Piezoelectrics		
	BaTiO ₃	PZT4	PZT5H	Pb(Zr,Ti)O ₃	PbNb ₂ O ₆	(Pb,Ca)TiO ₃	PZN (001)	PZN-8% PT (001)	PMN-35% PT (001)
$s_{11}^E (10^{-12} m^2 / N)$	8.6	12.3	16.5	9.6	15.6	7.3			
$s_{12}^E (10^{-12} m^2 / N)$	-2.6	-4.05	-4.78	-2.5	-4.7	-1.5			
$s_{13}^E (10^{-12} m^2 / N)$	-2.7	-5.31	-8.45	-4.6		-1.4			
$s_{33}^E (10^{-12} m^2 / N)$	9.1	15.5	20.7	13.2	19.8	8.5	48	130	10.2
$s_{44}^E (10^{-12} m^2 / N)$	22.2	39.0	43.5	34.2		18.1			
$d_{31} (10^{-12} C / N)$	-58	-123	-274	-64	-262	-3.2			
$d_{33} (10^{-12} C / N)$	149	289	593	164	583	68.2	1100	2500	1240
$d_{15} (10^{-12} C / N)$	242	496	741	390	730	70.5			
$\epsilon_{11}^T / \epsilon_0$	1300	1475	3130	1010		237			
$\epsilon_{33}^T / \epsilon_0$	1200	1300	3400	500	3450	209	3600	5000	3100
$\sigma_{12}^E (\%)$	30.2	32.9	29.0	26.0	26.7	20.5			
$\sigma_{13}^E (\%)$	30.5	38.5	45.7	40.9		17.8			
$\sigma_p^E (\%)$	51.6	66.5	76.7	67.2		28.2			
$k_{31} (\%)$	-19.4	-33.4	-38.8	-31.	-38.	-3.			
$kp (\%)$	-33.	-58.	-65.	-51	-64.	-4.			
$k_{15} = k_{11} (\%)$	-48.	71.	67.5	70.	68.	36.			
$k_{33} = \%$	48.	70	75.2	67.	75.	54.	85.2	93.8	92.3

Table I-1. Major Properties for Piezoelectric Materials (Continued)
(Source: References 4 and 5)

Material Parameter	Piezoelectric Ceramics					Piezoelectric Single Crystal		
	BaTiO ₃	PZT4	PZT5H	Pb(Zr,Ti)O ₃	PbNb ₂ O ₆	(Pb,Ca)TiO ₃	PZN (001)	PZN-8%PT (001)
$k_{13} = \%$	49.1	71.5	75.4	67.3		55.6		
$k_t(\%)$	38.4	51.3	50.5	51.		52.	0.493	0.541
$\tan \delta(\%)$	0.6	0.4	2	0.8	0.9	1.93	0.008	0.031
Q_m	400	500	65	790	15	920	40	39.5
$\rho(10^3 \text{ kg/m}^3)$	5.55	7.5	7.5	7.92	5.9	6.94		35.3

Legend for Table I-1: Definitions of Material Parameters

Parameter	Symbol Used in Table I-1	Definition
Elastic compliance	s^E	The ratio of the stress to strain under a constant electric field
Piezoelectric charge constants	d	The strain that occurs when the electric field is given
Dielectric constants	ϵ^T	The electric displacement that occurs when the electric field is given at constant stress
Poisson's ratio	σ^E	The ratio of the strain of polarization axis direction and the distortion of right angle direction to the polarization axis under a constant electric field
Coupling factor	k	The root of ratio of the generated mechanical energy to the given electric energy and shows the conversion capacity of energy
Dissipation factor	$\tan \delta$	The ratio of parallel resistance to parallel reactance on the equivalent electric circuit
Mechanical Q	Q_m	The sharpness of mechanical vibration in the resonant frequency
Density	ρ	The ratio of mass to volume in the material
Subscripts 11, 13, 33, and so forth	e.g., $\epsilon_{33}^T / \epsilon_0$	Crystallographic planes where the measurements are taken
Subscript "t"	e.g., k_t	Average material parameter

The remainder of this document will concentrate on areas where the single-crystal piezoelectrics can be substituted (based on the limited data available for single-crystal piezoelectrics) and on future applications of single-crystal piezoelectrics.

II. PIEZOELECTRIC MATERIALS APPLICATIONS

A. INTRODUCTION

Several applications have been developed to take advantage of the properties of the piezoelectric ceramic materials. Table II-1 (Ref. 10) lists some of the major applications in commercial and military areas.

Table II-2 gives piezoelectric properties that are important to different applications. Since the properties essential for the performance of one type of device may be irrelevant for the performance of other devices, the material properties of importance must be evaluated for each application.

Most of the current applications use lead zirconate titanate (PZT) as the piezoelectric ceramic material. However, depending on the device's required dielectric constant, the Curie temperature (or phase transition temperature) or other material parameters can be modified with dopants to match the requirements of a given application. Not only can composition be modified for a specific application but the size and shape of the piezoceramic can also be changed to accommodate a particular application. For example, some piezoceramics can be less than a 1-inch square while others are 3-inch diameter disks. There are no "absolute standards" with regards to size, composition, and performance. Essentially, each application drives the size, composition, and performance of the piezoceramic materials used for that application.

When the material properties of the piezoelectric ceramics and the single crystals are compared (see Table I-1), it appears that many current applications (see Table II-1) could benefit from a direct substitution of the single crystals for the piezoelectric ceramics. In fact, Toshiba (Ref. 9) has developed an echo cardiographic probe that provides better real-time imaging of the heart than the imaging provided by current probes. This improved imaging is a result of the large coupling factor of the PZN/PT crystal that Toshiba used in this application. For this case, a small crystal size was satisfactory. However, larger crystals (i.e., several centimeters) are needed for other applications but are unavailable at this time in any quality or quantity.

Table II-1. Current Piezoelectric Ceramic Applications in Various Industries
(Source: Reference 10)

Industry	Applications
Military	Hydrophones and sonobuoys Depth sounders Targets Fuse devices Telephony Sub-bottom profiling Sonar pingers Ring laser gyros Adaptive optics
Commercial	Ultrasonic cleaners, welders, and degreasers Thickness gauging Flaw detection Level indicators Ultrasonic drilling and ultrasonic imaging Geophones Delay lines TV and radio resonators Airplane beacon locators Ignition systems Fans Relays Ink jet printing Alarm systems Strain gauges Capacitors
Medical	Ultrasonic cataract removal Ultrasonic therapy Insulin pumps Fetal heart detectors Flow meters Disposable patient monitors Ultrasonic imaging Vaporizers
Automotive	Knock sensors Wheel balancers Radio filters Seat belt buzzers Tread wear indicators Air flow Fuel atomization Tire pressure indicators Spark ignition Audible alarms Keyless door entry
Consumer	Humidifiers Gas grill ignitors Telephones Smoke detectors Microwave ovens Jewelry cleaners Phonograph cartridges Sneakers Cigarette lighters Lighting security Musical instruments Ultrasonic sewing

Table II-2. Important Properties for Piezoelectric Device Applications
(Source: References 2,10)

Application	Property of Importance
Ultrasound imaging (medical)	Large strain in small fields High electromagnetic coupling Low frequency
Non-destructive evaluation (NDE)	High frequency
Piezoelectric valves	High stiffness High mechanical resonance
Actuators	
Deformable mirrors (adaptive optics)	Long-term stability; large strain
Mechanical micropositions	Reproducibility Anhysteretic behavior
Impact devices	Quick responses Large electromagnetic coupling Large generative force
Suspension systems [e.g., cars (Toyota)]	Rapid response
Transducers	
Micropositioners	Electromechanical coupling Electrical impedance
Moonies	High hydrostatic piezoelectric and voltage coefficients
Electrostrictive: adaptive optics, precision microprocessors	High electromechanical coupling coefficient; no hysteric behavior at high fields
Gas injection system (piezoelectric valves and sensors)	High response
Sonar transducers	Large stress, higher frequency
Guidance devices	Mid-frequency operating ranges
Capacitors	High dielectric strength; low dissipation factor

B. COMMERCIAL APPLICATIONS

Although Table II-1 lists the commercial and military uses of piezoelectric ceramic materials separately, many commercial uses (e.g., ultrasonic imaging, relays, or resonators) are also possible military applications. In other words, some applications for piezoelectric ceramic materials might be "dual-use." The commercial industry, however, drives the price and demands of such components.

The largest commercial industry for piezoelectric ceramics is the capacitor industry (Ref. 11). Single-crystal piezoelectrics could readily impact this area because of the single crystals' high permittivity and nonlinear behavior at high fields. However, using single crystals for this or other applications increases the voltage requirement. Most piezoelectric ceramic commercial applications only need several hundred volts to drive their systems. Single crystals require on the order of several thousand volts. Another problem with substituting single crystals in current applications is the crystals' low mechanical properties.

Table II-3 compares the properties of polycrystalline piezoelectric materials and single-crystal piezoelectrics for specific systems. Most of the key properties of the single-crystal piezoelectrics are available, but many have not been determined. For these particular uses, the properties of the single crystals that are superior to the properties of polycrystalline ceramics are the extremely low dissipation factor or dielectric losses and the high coupling and high piezoelectric charge constant or stress. However, the mechanical properties of the single crystals are a factor of 10 lower than those given for the polycrystalline ceramics. This could be caused by impurities and other inclusions that would result in lower mechanical properties. Given the high power requirements, low strength, and missing property parameters, a direct substitution of the single crystals for piezoelectric ceramic devices could probably not be achieved without redesigning the current system or relinquishing some properties of the single crystals.

C. MILITARY APPLICATIONS

The Services' military applications—like each of the commercial applications—have different requirements for piezoelectric materials. The Navy is the largest user of piezoelectric materials, mainly in sonar and acoustic imaging systems. The Air Force uses piezoelectric materials in the adaptive optics area for the Space-Based Laser (SBL) and Airborne Laser (ABL) systems. The Army has only had limited requirements for piezoelectric devices (e.g., fuzes for anti-tank munitions) other than those available commercially.

For piezoelectric materials, new areas of interest have been generated by the ability to tailor properties and by the development of new processing techniques. Some of these areas include applications for vibration control and suppression in aircraft, structural health monitoring (which, in the future, will decrease operation and support costs for the military), fuzing and safing warheads, miniature microphones, and biochem sensors. Some of

Table II-3. Comparison of Conventional and Single-Crystal Piezoelectric Properties
(Source: References 9,12)

Material Characteristics		Main Uses			
		Ultrasonic Sonar Humidifier	Actuator	Ultrasonic Detector (Medical Instruments)	Single Crystal PZN-8% PT
Coupling factors	$\times 10^{-2}$	K_p	56	6	
		K_{31}	32	6	
		K_{33}	62	47.1	94
		K_t	43	43	
		K_{15}	47	*	
Frequency constants	$m_{1/2}$	N_p	2030	2800	
		N_{31}	1450	2150	
		N_{33}	1400	2150	
		N_t	1940	2250	1401
		N_{15}	960	*	
Relative dielectric constant		$\epsilon_{11}^T/\epsilon_0$	4700 \pm 500	*	
		$\epsilon_{33}^T/\epsilon_0$	6300 \pm 630	220 \pm 20	4200
Piezoelectric charge constants	$\times 10^{-12}$ m/V (C/N)	D_{31}	-300	-4.7	
		D_{33}	600	58.2	2070
		D_{15}	1400	*	
Piezoelectric voltage constants	$\times 10^{-3}$ V-m/N (m^2/C)	g_{31}	-5.6	-2.4	
		g_{33}	11	30.3	
		g_{15}	13		

Table II-3. Comparison of Conventional and Single-Crystal Piezoelectric Properties (Continued)
(Source: References 9,12)

Material Characteristics		Main Uses			Single Crystal PZN-8% PT
		Ultrasonic Sonar Humidifier	Actuator	Ultrasonic Detector (Medical Instruments)	
Youngs modulus	$\times 10^{10}$ N/m ²	Y_{11}^E	6.4	13.9	
		Y_{33}^E	6.0	14.4	0.9
		Y_{55}^E	2.7	*	
Poisson's ratio		σ	0.34	0.2	
Mechanical Q		Q_m	20±10	1450±400	39.5
Dissipation factor	%	$\tan \delta$	5.2	1.5	0.017
Curie point	°C	T_c	140	310	170
Density	$\times 10^3$ kg/m ³	ρ	7.7	7.4	
Temperature coefficient	°C	-20-20 °C	7500	2550	
	(ppm/°C)	20-60 °C	11000	4000	

these applications have been tested but have not been fielded. Some single-crystal piezoelectric material properties exceed some of the developmental ceramic materials' properties for these new applications. However, as is the case with commercial applications, the voltage requirements for the single-crystal material are greater than what is available on most ships, aircraft, and other military vehicles. Although other aspects of the single crystals must also be addressed, the voltage requirement is the most significant issue for the military.

III. DEVELOPMENT PROGRAMS

Research in piezoelectric materials has been ongoing since the 1950s. Most of the research has been conducted on piezoelectric ceramics, with some emphasis in the last few years on thin-film polymers and single-crystal piezoelectrics. Table III-1 lists programs awarded funding during fiscal years (FYs) 1994 to 1996.¹ Appendix A provides additional details for each program.

Table III-1. Piezoelectric Programs Funded From 1994 to 1996
(Source: Reference 13)

Agency	Piezoelectric Actuator Programs	Appendix A Reference
National Science Foundation (NSF)	Methods for Performance Enhancement of High-Speed Flexible Mechanisms With Multiple Joint Clearances	Para. A.1, p. A-3
NSF	Active Self-Tuning Vibration Control of Machine Tools Using Dynamic Absorbers	Para. A.2, p. A-3
NSF	Proof-of-Concepts Study of Piezoceramic C-Block Actuators	Para. A.3, p. A-4
Department of Defense (DoD) (Army)	Waves and Vibration in Electroplated Piezoelectric Plate and Substrate Systems	Para. A.4, p. A-4
DoD (Army)	A Structural Damping Technique Based On Coupling Structures With Electronic Circuits	Para. A.5, p. A-5
DoD (Army)	Modeling and Analysis of Composites Using Smart Materials Optimization Techniques	Para. A.6, p. A-5
DoD (Army)	Flexible Fabrication of High-Performance Piezoelectronic Actuators by Injection Molding	Para. A.7, p. A-6
DoD (Navy)	A Versatile Positioning System for Scanning Probe Microscopy	Para. A.8, p. A-7
DoD [Defense Advanced Research Projects Agency (DARPA)]	Synthesis and Processing of Intelligent Cost - Effective Structures (SPICES)	Para. A.9, p. A-7
DoD (DARPA)	Submicron Lithography With the Atomic Force Microscope (AFM)	Para. A.10, p. A-7
National Space and Aeronautics Administration (NASA)	Injection Molded, High-Performance Piezoelectric Actuators	Para. A.11, p. A-8
Department of Energy (DOE) (Sandia)	Advanced Submarine Technology	Para. A.11, p. A-8

¹ Programs that have been supported since FY 1996 were not available in Carroll's Defense database.

Table III-1. Piezoelectric Programs Funded From 1994 to 1996 (Continued)
(Source: Reference 13)

Agency	Piezoelectric Transducer Programs	Appendix A Reference
DoD (Army)	Silicon Carbide Microsensor With Piezoresistive Diamond Sensing Elements	Para. B.1, p. A-8
DoD (Navy)	Domain-Controlled High-Power Piezoelectric Transducer Materials	Para. B.2, p. A-8
DoD (Navy)	Transducer Modeling	Para. B.3, p. A-9
HHS	Broad Spectrum Numerical Simulators for Bioengineering	Para. B.4, p. A-9
HHS	Cognitive Psychophysiological Studies in Post-Traumatic Stress Disorder (PTSD)	Para. B.5, p. A-9
NSF	Electromechanical Finite Element Models for Ultrasound Transducer Analysis and Design	Para. B.6, p. A-10
NSF	Laser Crystallization of Spin-On Ferroelectric Thin Films for Nonvolatile Random Access Memories (RAMs)	Para. B.7, p. A-10
NSF	Systematic Prediction and Characterization of New Ferroelectric Materials	Para. B.8, p. A-10
Agency	Relaxor Ferroelectric Materials Programs	Appendix A Reference
DoD (Navy)	First-Principles-Based Calculations of Phase Diagrams and Cation Ordering Phenomena of Some Relaxor Ferroelectrics	Para. C.1, p. A-11
Agency	Piezoelectric Ceramic Programs	Appendix A Reference
DoD (Navy)	Near Net-Shape Fabrication of Ultrafine Piezoelectric Ceramic/Polymer Composites for Undersea Ultrasonic Imaging	Para. D.1, p. A-11
DoD (Navy)	Distributed Electroceramic Composite Actuation for Active Structural Control	Para. D.2, p. A-11
DoD [Office of the Secretary of Defense (OSD)]	Development of Fine-Scale Piezoelectric Ceramic/Polymer Composites by Fused Deposition Process	Para. D.3, p. A-12
DoD (Navy)	Fine-Scale Piezoelectric Ceramic/Polymer Composites via Fused Deposition Process	Para. D.4, p. A-12
NSF	Multiple-Scale Micromechanics of Polycrystalline Piezoelectric Ceramics	Para. D.5, p. A-12
NSF	Tactile Computer Reader for Knowledge Representation	Para. D.6, p. A-12
Agency	Single-Crystal Piezoelectric Programs	Appendix A Reference
DoD (Navy)	Workshop on Ferroelectric Single Crystals With High Electromechanical Coupling: Growth, Characterization, and Applications	Para. E.1, p. A-13

The programs listed in Table III-1 range from theoretical calculations and predictions of piezoelectric properties to manufacturing methods to device characterization. The Navy supports most of the programs. The Department of Health and Human Services (HHS) is another large supporter for piezoelectric materials R&D. The HHS focus is on ultrasonic imaging. Most these programs still emphasize the development of piezoelectric ceramics.

Other areas of research that have been supported in the last 2 years include:

- Phased array antennas that use thin-film ferroelectrics as phase shifters
- Two-dimensional (2-D) arrays that use ferroelectric materials for the bias-controlled transducers
- Vibration control, where either stacked piezoelectric actuators or piezoelectric fiber patches are used in aircraft, rotorcraft, satellites, and space structures
- Sonar where MicroElectroMechanical Systems (MEMS)-based devices incorporate PZT thin films in transducer devices
- Ferroelectric polymers for broadband detection of surface acoustic waves (SAWs)
- Non-destructive interrogation (NDI) on critical structural components using an impedance-based approach with a PZT wafer attached to an area of interest
- Micropumps that use PZT thin films for actuation
- Microwave and infrared (IR) detectors that use ferroelectric thin films with MEMS devices
- Next-generation telescopes that use stacked ferroelectric actuators to increase focusing capability.

These programs differ from the programs listed in Table III-1 because most of the materials being studied are not traditional ceramic materials.

Should single-crystal piezoelectrics be used in these programs rather than the materials that are currently being studied for the various applications? The answer is questionable. If the single-crystal piezoelectrics can meet the requirements of the systems being developed (i.e., power, packaging, and reliability), the single-crystal piezoelectrics would be more feasible than the polycrystalline piezoelectrics under development because of their higher strain capability and lower dielectric losses. It is the author's opinion, however, that until consistent single-crystal piezoelectric materials are produced, the existing piezoelectric programs should continue to focus on the more traditional materials in the original program

plans. As better manufacturing techniques are developed and consistent data are obtained in the single-crystal piezoelectric programs, all piezoelectric programs should be re-evaluated to determine if single-crystal piezoelectric materials would have a greater impact than any of the other materials currently being developed. This evaluation would also have to consider the constraints in using these materials (e.g., size, availability on a large scale, power requirements, mechanical properties, and temperature dissipation).

IV. NOVEL USES FOR PIEZOELECTRIC MATERIALS

New uses for piezoelectrics are possible given the high strains and other piezoelectric properties that are known for single-crystal piezoelectrics at this time. For example, new actuator designs could take advantage of the large strain properties of the single-crystal piezoelectric materials and be used to release munitions instantaneously from gun barrels or aircraft pylons. The Navy held a workshop in November 1996 to discuss the potential of high-performance single-crystal piezoelectrics in Navy applications. The memorandum in Appendix B summarizes the results of this workshop.

Single-crystal piezoelectrics could also benefit the other Services. Representatives from all the Services and NASA were invited to participate in a small workshop at the Institute for Defense Analyses (IDA) on April 29, 1998, to explore new uses of piezoelectric materials. The results of this IDA workshop were categorized into six areas: power conversion, sensors, optics, actuators, human factors, and systems. Table IV-1 lists these areas and the applications in which the participants of the IDA workshop believed single-crystal piezoelectric materials would have the greatest impact.

The following are some general comments for each of the categories:

- **Power conversion.** Properties of the single-crystal piezoelectric materials would be useful in converting mechanical energy to electrical energy. One example from the list is the micro-strip antenna. Radio frequency (RF) energy would be translated into acoustics. Some applications are already being studied. The participants felt that single crystals may be more efficient than the current ceramics because of the lower dielectric losses.
- **Sensors.** Some of the applications are improvements in current systems, such as health-monitoring sensors. Load sensors would translate an impact into an electrical signal that, in turn, would control actuators to dampen vibration in cars or tanks.
- **Optics.** Single crystals for gun sights would act to stabilize vibration. Piezoelectric ceramic materials are currently used as actuators in deformable mirrors. Although this would be a substitution rather than a new use for piezoelectrics, the participants believed that the single crystals would provide a faster response than conventional ceramics.

Table IV-1. Novel Military Uses for Single-Crystal Piezoelectric Materials

Area	Applications
Power conversion	Boat hull skins that generate electric power on boats Person power converted to electrical power Power projectiles Wing motion converted to electrical power Wave motion converted to electrical power Power recovery from mechanical devices (vibration, friction, and thermal) Micro-strip antenna Electric cars
Sensors	Structural health monitoring sensors that are built into material and give larger signals than current NDE sensors Microphones for sensing shock waves Load sensors Mast-mounted sight for micropositioning
Optics	Deformable mirrors Electro-optical acoustic applications to control jitter Gun sights
Actuators	Micropositioning gun barrels or telescopes Biomechanical enhancement for insects (e.g., insect wings assisted with actuators) Fine adjustment at tool heads Projectile control Ejector actuator for munitions Micropumps for vacuum systems Propless propulsion Active propeller and turbine blades Variable compliance gun stock Flutter detection in wing tunnel tests Wing twist/rotary twist Internal actuation within a structure Active air foil damping RF MEMS devices where piezoelectric films are used for actuation Controlling kinetic energy projectiles by changing the shock wave Microminaturization revisited
Human factors	Inflatable inner soles of shoes Micro-pumps (self-contained air conditioner) Lumbar seat control (back support that conforms to different conditions) Breathing fabric "Superman suit"
Systems	Modified beam rider Shape-change antenna Mini high-cycle fatigue machines Acoustic refrigerators Shear rate monitoring in molding process Noise and vibration reduction systems in machinery Micro-unmanned aerial vehicles (MAVs) Shark skins for variable geometry Turbine engine inlets Active control in weapon systems Localized ultrasonic energy source in composite processing

- **Actuators.** From the list shown in Table IV-1, the only identified substitution of single crystals for ceramic actuators would be in the flutter detection in wind tunnel tests, wing twist/rotary twist,² and the RF MEMS devices. The other areas listed under actuators are new and fairly novel ideas that the group suggested specifically for single-crystal materials.
- **Human factors.** These areas were some of the most novel areas, with the exception of the inflatable inner soles. The breathing fabric and the "Superman suit" are slightly different concepts. The breathing fabric would consist of many MEMS devices that would open and close openings in protective clothing. The single-crystal actuators would close the MEMS devices if the MEMS device detected a chemical or biological agent. The "Superman suit" was envisioned to be a pressurized suit in which a single-crystal film would constrict over muscles, thus providing more strength for a person lifting an object.
- **Systems.** Acoustic refrigerators, turbine engine inlets, and noise and vibration reduction systems are currently using other types of piezoelectric materials or actuator materials. Again, substituting single-crystal piezoelectric materials may allow for new, more efficient designs that could not have been considered previously.

The IDA workshop participants identified power conversion, actuators, and systems as the categories that would have the most impact on the military. Within the other categories, the optical gun sights and the micropumps for a self-contained air conditioner were considered applications that would intrigue the military.

All the novel uses for single-crystal piezoelectrics assumed that the single crystals were perfect, readily available, and characterized. However, this is not the case. In addition to large power requirements and reliability issues, growing a crystal using the refluxing method takes nearly 2 weeks (Ref. 5). This long process time is not conducive to a manufacturing environment. Also, aging issues have not been addressed.

The workshop participants developed a list of single-crystal piezoelectric issues. These issues focused on what is needed to use single crystals in the applications identified in the workshop:

- Manufacturability: size, orientation, quantity, other forms (such as single-crystal fibers)
- Quality standards to yield consistent material

² This is still in the developmental stage. It has not been fielded yet.

- Uniform aging characteristics
- Electrical and mechanical biasing
- Stackability
- Linear performance in temperature ranges for military usage
- Coupled/dynamic modes
- Hazardous waste concerns
- Sensitivity to other materials
- Internal power dissipation (must be efficient)
- High-temperature capability/sensitivity
- Parallel crystal growth with silicon and sapphire for devices
- Weight
- Built-in pre-stress for crystals
- Cost (in comparison to conventional ceramics)
- Cutting of crystals
- Existent suppliers.

The two most important issues for the single-crystal materials were manufacturability (size, orientation, and so forth) and quality standards that would yield consistent materials. Other obvious issues that need to be addressed, such as packaging, electroding, and temperature tolerance, may be covered to some extent under current programs and were not considered problem areas by the participants.

Finally, the workshop participants identified the important commercial applications of the single-crystal piezoelectric materials (see Table IV-2). The sporting industry was determined to be one of the larger beneficiaries. The medical industry (mainly in rehabilitation and not in ultrasonics) would also benefit. If single-crystal piezoelectric materials are to compete in the market, however, an industrial base of single-crystal products is needed. At the present time, universities and small businesses are providing a few crystals per month to current research programs. Larger volume single-crystal manufacturers will not only provide more crystals but, as a consequence of availability, will also reduce the cost of these materials. Also, material quality will be more consistent in these larger batches.

Table IV-2. Commercial Applications for Single-Crystal Piezoelectric Materials

Area	Applications
Sports	Inner soles and lights on shoes Mountain bikes that have smoother rides and automatic lighting Active fin for wind surfing Assisted tennis rackets and golf clubs Backpacks with built-in shock absorbers
Medical	Rehabilitation medicine (micropumps to move legs) Assisted walking devices Orthopedic implants Active braces
Optical	Adaptive optics for microscopes Glasses that can change focal length Adaptive optics for shooting sports
Transportation	More sensitive accelerometers for cars Active suspensions (high force, high strain) Embedded crystals in tires Active damping for shock loads for trains Micropumps in cars (to replace hydraulics)
Miscellaneous	Acoustic refrigerators

V. CONCLUSION

Studies of single-crystal piezoelectrics began as early as the 1960s. Initial studies were limited to property measurements on very small crystals, and were questionable. In recent years, larger crystals (but still less than 1 inch in the largest dimension) have become available and enable more reliable property measurements. These property measurements indicate that the single-crystal materials have better piezoelectric properties than more conventional polycrystalline ceramics.

After reviewing the literature, it was concluded that insufficient data on single-crystal piezoelectrics exist to warrant a re-direction of current piezoelectric ceramics programs toward using single-crystal piezoelectrics. Also, in addition to the insufficient data for single-crystal piezoelectric properties, constraints in using single-crystal materials must be considered. These constraints include size, availability on a large scale, comparatively low mechanical properties, and large voltage requirements.

The IDA-sponsored workshop produced a list of potential new uses for the single-crystal piezoelectric materials and a list of new issues that need to be addressed to use single crystals in the novel applications identified. If these issues are not addressed, it is the author's opinion that single-crystal piezoelectrics will not be fielded in either commercial industry or in the military.

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GLOSSARY

2-D	two-dimensional
3-D	three dimensional
ABL	Airborne-Based Laser
AFM	Atomic Force Microscope
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DoD	Department of Defense
DOE	Department of Energy
DSO	Defense Sciences Offices (DARPA)
ECG	electrocardiography
EEG	electroencephalography
EMG	electromyography
FNVRAM	ferroelectric nonvolatile random access memory
FY	fiscal year
HHS	Department of Health and Human Services
IDA	Institute for Defense Analyses
IR	infrared
MAV	micro-unmanned aerial vehicle
MEMS	MicroElectroMechanical Systems
NASA	National Space and Aeronautics Administration
NDE	non-destructive evaluation
NDI	non-destructive interrogation
NIH	National Institutes of Health
NRL	Naval Research Laboratory

NSF	National Science Foundation
OSD	Office of the Secretary of Defense
PMN	lead magnesium niobate
PMN/PT	lead magnesium niobate/lead titanate
PST	lead scandium tantalate
PTSD	Post-Traumatic Stress Disorder
PZN/PT	lead zinc niobate/lead titanate
PZN	lead zinc niobate
PZT	lead zirconate titanate
R&D	research and development
RAM	random access memory
RF	radio frequency
SAW	surface acoustic wave
SBL	Space-Based Laser
SOW	Statement of Work
SPICES	Synthesis and Processing of Intelligent Cost Effective Structures (DARPA program)
VLSIC	Very Large Scale Integrated Circuitry

**APPENDIX A. FISCAL YEAR (FY) 1994 TO 1996 AWARDS
AND TASK ABSTRACTS**

APPENDIX A. FISCAL YEAR (FY) 1994 TO 1996 AWARDS AND TASK ABSTRACTS

Note: *Table III-1 identifies the sponsoring agency.*

A. PIEZOELECTRIC ACTUATOR PROGRAMS

1. Methods for Performance Enhancement of High-Speed Flexible Mechanisms With Multiple Joint Clearances

This research explores an efficient modeling, design, and control method for high-speed flexible machines. Impacts within the clearances of such devices can seriously degrade performance and generate excessive noise and vibration. Researchers in this program model the dynamic behavior of machines by incorporating design parameters, such as link elasticity, link lengths, clearance values, and material properties. Practical methods are developed to reduce and control the effects of clearances through (1) the optimal use of geometric and material properties, (2) an on-line technique for clearance estimation and diagnostics using machine vibration response, and (3) an innovative application of piezoelectric actuators and sensors bonded to the machine links to suppress clearance-induced vibration and impact forces. A coordinate reduction procedure, in conjunction with the methods of finite element and harmonic balance, is used to assist in arriving at optimal designs of flexible mechanisms.

2. Active Self-Tuning Vibration Control of Machine Tools Using Dynamic Absorbers

This research focuses on the development of techniques for controlling chatter and vibration in machining by using an actively controlled dynamic absorber. The inertial force generated by actuation of the secondary mass relative to the cutting tool assembly modifies the systems' dynamic characteristics. The proof-of-concept design, using a piezoelectric actuator packaged inside of the boring bar, has been demonstrated to be effective. The research will provide an enhanced theoretical basis for the approach and extend its range of application to a wider variety of practical machining conditions. In particular, robust controller methodologies will be investigated, and the system design parameters will be opti-

mized. Higher force and higher stroke capabilities will be sought in the boring operations. An extension to multi-point machining, such as milling, will also be considered. Successful completion of the research should enable a stable operation of boring bars with higher length-to-diameter ratios. Material removal rates and accuracies in boring and milling operations will be improved.

3. Proof-of-Concepts Study of Piezoceramic C-Block Actuators

This research focuses on evaluating the concept of C-block piezoelectric actuator design. C-block actuators are curved composite beams with at least two layers of piezoelectric materials. These materials have the potential for generating larger forces and orders of magnitude than equivalent polymeric stacks. This project will design, build, and test a C-block actuator for its static and dynamic performance. Such actuators have applications in the aerospace, automotive, health and rehabilitation, and manufacturing fields.

4. Waves and Vibration in Electroplated Piezoelectric Plate and Substrate Systems

This research focuses on:

- Investigating the electromechanical interactions in a piezoelectric actuator-substrate system
- Predicting the resonant frequencies and distributions of stresses, displacements, and electric potential
- Studying the sensitivity of the frequency and deflection caused by applied forces, acceleration, or added mass
- Developing an understanding of the effect of the quantities cited in the previous step on the deflection and frequency sensitivity of the system in preparation for the application of the piezoelectric actuators or sensors in smart structures and microelectromechanical systems (MEMS)
- Treating the actuator-substrate system as consisting of two parts:
 - The electroplated piezoelectric plate (the actuating part)
 - The substrate layer that can be isotropic, anisotropic, or piezoelectric (the actuated part)
- Bonding the parts together at the contacting face to form the system and excite it by an impressed voltage across the electrodes
- Deriving a set of two-dimensional (2-D) governing equations of the coupled fields with the following advantages:

- Keeping the identities of material properties, stress, displacement, and electric potential for each constituent layer
- Satisfying the interfacial continuity conditions for displacements, tractions, and potential
- Being able to accommodate the analysis of plates with finite boundaries.

5. A Structural Damping Technique Based On Coupling Structures With Electronic Circuits

This research focuses on:

- Implementing a novel structural damping technique based on coupling structures with electronic circuits to suppress free and forced vibrations of elastic composite beams
- Extending the active composite cantilever beam model to include inertial forces caused by high-speed rigid body rotation of a hub in the simulation of a set of helicopter rotor blades
- Extending the method developed earlier by the subcontractor to suppress single-mode free and forced torsional and flexural vibrations of elastic laminated composite beams with integrated piezoelectric actuators and sensors
- Developing a theory for the dynamics of these beams—a theory that accounts for the elastic coupling caused by anisotropy, piezoelectrically induced strains, and transverse shear deformations
- Developing a control strategy to couple quadratically the beamwidth and an electronic circuit whose frequency can be adjusted to be one-half of one of the natural frequencies of the beam
- Performing numerical simulations to determine the optimal gains for the controller and, later, to validate and refine the effectiveness of the control strategy
- Using the beam-electronic circuit model to investigate the control of a beam rotating with constant speed and subjected to harmonic disturbances.

6. Modeling and Analysis of Composites Using Smart Materials Optimization Techniques

This research focuses on:

- Developing an accurate analytical model for proper formulation of composite structures with embedded actuators and sensors—taking into account the discontinuities caused by the presence of the embedded and distributed

actuators in the primary structure and including the effects of transverse shear deformation and the presence of imperfections caused delaminations of arbitrary shape and size.

- Applying the higher order composite plate theory formulation to the analysis of a rotating composite box beam with embedded piezoelectric sensors and actuators.
- Integrating the coupled structure-controller problem by developing a formal structure/controller optimization procedure that includes all the necessary design criteria.
- Determining the optimal structure-controller designs that lead to reduced levels of vibratory loads and increased levels of structural damping in helicopter rotor systems built around active composite box beams. This research is relevant to helicopter active control rotors, resulting in payoffs and goals reflected in the Department of Defense (DoD) technology goals/payoffs for rotary wing vehicles (i.e., improved maneuverability/agility, reduced signature, increased lift-to-drag ratio, reduced maintenance costs, reduced vibration, increased pilot effectiveness, and increased mission effectiveness/range).
- Developing a new composite plate model with embedded piezoelectric actuators based on a higher order plate theory that accounts for material discontinuities, providing experimental validation for the developed model, and extending the developed model to a composite box beam formulation.
- Formulating a hybrid optimization procedure to include multiple objective functions and constraints using continuous and discrete design variables.
- Developing the coupled optimization procedure for vibration reduction of a composite box beam, including controller-structure interaction.
- Conducting experiments to validate the models.

7. Flexible Fabrication of High-Performance Piezoelectronic Actuators by Injection Molding

This research focuses on adapting a proprietary net-shape ceramics injection-molding technology for the fabrication of two new families of reliable, higher performance piezoelectric actuators for use in active control of rotorcraft blade trim tabs and aircraft wing surfaces. The new piezoelectric actuator configurations will offer enhanced force-displacement characteristics that will extend the capabilities of smart materials and structures in the active control of helicopter rotor blade trim tabs. These actuators will be able to operate over wider frequency and temperature ranges than current devices.

This program will consist of four principal tasks:

1. Design reviews for the design of net-shape molded actuators suitable for test by McDonnell Douglas
2. Net-shape actuation fabrication and performance verification
3. Net-shape actuator down-selection, refinement, and performance evaluation
4. Actuator manufacturing, including bench/whirl test demonstrations and wind tunnel testing.

8. A Versatile Positioning System for Scanning Probe Microscopy

The objective of this program is to design and fabricate a fast, high-accuracy translation system suitable for a nanolithography instrument to fabricate ultradense electronic circuitry. A two-stage translation system will be designed and fabricated. This system will use piezoelectric actuators and a laser interferometric position sensor with servo loop control to achieve the required positional accuracy and scanning speed.

9. Synthesis and Processing of Intelligent Cost-Effective Structures (SPICES)

The overall program objectives are to develop and demonstrate an economical material processing and fabrication system for intelligent polymeric structures. The Naval Research Laboratory (NRL) role will be to provide technical leadership and guidance in the areas of sensor and actuator selection and implementation and to apply heterogeneous constitutive models in the analysis for such structures. NRL's approach is fully documented in the Statement of Work (SOW). It entails piezoelectric actuator synthesis and manufacturing technologies development and optical sensor and embedment technology development. Also, analytic support is provided through mathematical synthesis of macroscale constitutive relations for composite materials.

10. Submicron Lithography With the Atomic Force Microscope (AFM)

The objective of this program is to develop a practical new method for fabricating electronic circuits with submicron feature sizes. This approach uses amorphous silicon as the resist material and an AFM operating in air as the exposure tool. Large arrays of independently controlled AFM cantilever/tips will be developed to increase throughput. Each element will contain an integrated piezoelectric actuator and piezoresistive deflection sensor.

A suitable control system for operating the array will be developed, and several nanoscale devices will be fabricated as a demonstration of the technique.

11. Injection Molded, High-Performance Piezoelectric Actuators

A write-up for this program was not available.

12. Advanced Submarine Technology

A write-up for this program was not available.

B. PIEZOELECTRIC TRANSDUCER PROGRAMS

1. Silicon Carbide Microsensor With Piezoresistive Diamond Sensing Elements

The objective of this program is to develop an integrated pressure transducer and to demonstrate high-temperature pressure measurements using diamond and beta-sic as the sensor materials in the 500 to 800 C°temperature range. This research is relevant to the DoD's requirement for pressure transducers that can provide measurement in the high-temperature portions of compressors, turbines, jet and rocket engines, and ground vehicle engines. Higher temperature pressure measurements contribute to improvements in performance, safety, and fuel efficiency. The proposed sensors have wide applicability in commercial and military systems.

This program has two major thrusts.

1. Fabrication technologies will be developed for these materials. These technologies will provide for processing of piezoresistive elements in β -SiC and in diamond. This includes metallization, etching, doping, and ohmic contacts, which will allow the sensing elements to be placed in a four-arm wheatstone bridge with millivolt output and pressure.
2. Prototype sensing elements will be integrated on a pressure diaphragm structure to test the performance of the transducers at elevated temperature.

2. Domain-Controlled High-Power Piezoelectric Transducer Materials

The objective of this program is to deepen the basic understanding of ferroelectricity and apply that understanding in optimizing materials for piezoelectric and electrostrictive actuator devices. The research will focus on:

- Synthesizing, characterizing, and modeling ferroelectric materials

- Performing fundamental theoretical and experimental investigations of the ferroelectric phase transition
- Understanding the tricritical behavior in materials systems exhibiting a morphotropic phase boundary, such as lead zirconate titanate (PZT)
- Separating intrinsic and extrinsic contributions to the material properties of ceramic ferroelectrics.

Researchers will use the basic understanding gained in this research to optimize the performance of ferroelectric materials used for sonar transducers, surface acoustic wave (SAW) materials for analogue signal processors, and electro-optic materials for opto-electronic signal processors.

3. Transducer Modeling

The objective of this program is to investigate the theoretical modeling of piezoelectric and electrostrictive composite materials for sonar transducer applications and to develop a computer model of various piezoelectric and electrostrictive composite materials.

4. Broad Spectrum Numerical Simulators for Bioengineering

This software development project will produce, disseminate, and support an important class of numerical modeling resources for National Institutes of Health (NIH)-funded academic bioengineering research groups. The suite consists of three-dimensional (3-D) finite element/finite difference computer modeling codes for ultrasound propagation and scattering, piezoelectric transducers, transient thermal effects, material nonlinearities, large-deformation elasticity, electromagnetic propagation and scattering, and incompressible fluid flow. These modeling capabilities are computer intensive, the algorithms are numerically sophisticated, and the codes must provide many ancillary capabilities to be effective (e.g., model building, visualization, signal processing, and so forth).

5. Cognitive Psychophysiological Studies in Post-Traumatic Stress Disorder (PTSD)

The broad aim of this program is to examine brain electrical activity associated with exposure to trauma-related stimuli in persons suffering from PTSD. Event-related potential methods will be used to examine time-locked, scalp-recorded electrical activity at high temporal resolution.

Subjects will be tested with a recording montage that includes between 4 and 60 channels of scalp electroencephalography (EEG). Also recorded will be one channel of scalp electromyography (EMG) (left temporalis) and two channels of facial EMG (left corrugator supercilii and left zygomaticus major), as well as electrocardiography (ECG) (lead I) and respiratory effort. EMG and ECG will be recorded via disposable Ag/AgCl electrodes, and respiratory effort via an abdominal band/piezoelectric transducer.

6. Electromechanical Finite Element Models for Ultrasound Transducer Analysis and Design

Medical ultrasound works by illuminating the body's interior with short, high-frequency sound pulses, receiving the echoes, processing them numerically, and displaying the moving image in real time on a monitor. The heart of ultrasound is a rather sophisticated composite transducer. With this sophistication, conventional design methods are approaching practical limits of effectiveness. Comprehensive computer modeling is viewed as the answer. The industry is currently using frequency-domain finite element codes exclusively, with limited success, in part, because of the transient character of the signals modeled. A much better alternative is explicit time-domain simulation. In the Phase I project, a time-domain finite element code, FLEX, was developed and validated for transient analysis of piezoelectric transducers and general wave propagation. It includes complete and operational piezoelectric, acoustic, and elastic elements. The proposed Phase II project will extend and tailor the code to the special needs of practicing design engineers. This research and development (R&D) is essential if the technical and marketing potential of this computer modeling system is to be achieved during the present window of opportunity.

7. Laser Crystallization of Spin-On Ferroelectric Thin Films for Nonvolatile Random Access Memories (RAMs)

This program addresses laser crystallization of spin-on ferroelectric thin films for applications in ferroelectric nonvolatile random access memories (FNVRAMs). This process affords precise control of temperature in the fabrication of PZT ferroelectric thin films on large-area, aluminized silicon wafers. Commercial applications of the technology included Very Large Scale Integrated Circuitry (VLSIC) manufacture and production of FNVRAMs, SAW filters, high-speed packages, piezoelectric transducers, pyroelectric sensors, and electronic and electro-optic devices.

8. Systematic Prediction and Characterization of New Ferroelectric Materials

This project is focused on establishing an interdisciplinary, undergraduate research laboratory for the systematic prediction and characterization of new inorganic ferroelectric materials. The 3-year project is expected to increase significantly the number of known ferroelectric materials, which now number about 200. Ferroelectrics are increasingly important in the fabrication of electro-optic devices, integrated circuits, pyroelectric detectors, and piezoelectric transducers. This project involves the prediction of ferroelectric behavior in new materials—predictions based on analyzing previously published crystallographic data; observing the high-temperature formation of these materials in polycrystalline form; verifying by X-ray analysis that the materials have the expected structure; processing specimens; and measuring the dielectric and thermodynamic properties of these materials as a function of temperature to confirm the predicted ferroelectric property.

C. RELAXOR FERROELECTRIC MATERIALS PROGRAMS

1. First-Principles-Based Calculations of Phase Diagrams and Cation Ordering Phenomena of Some Relaxor Ferroelectrics

The objective of this program is to understand the microphysics—cation ordering, in particular—of technologically important relaxor ferroelectric material systems and to lay the theoretical groundwork for exploring new material systems. This program will devise and apply first principles theoretical approaches to the study of relaxor ferroelectrics—in particular, cation ordering in lead scandium tantalate (PST) and lead magnesium niobate (PMN).

D. PIEZOELECTRIC CERAMIC PROGRAMS

1. Near Net-Shape Fabrication of Ultrafine Piezoelectric Ceramic/Polymer Composites for Undersea Ultrasonic Imaging

The objective of this program is to devise materials synthesis and processing techniques to fabricate fine-scale piezoceramic structures and piezoceramic/polymer composites and assess their benefits as transducer materials for undersea ultrasonic imagers. This program will also explore the extension of injection-molding techniques for piezoceramics with spatial scales and microstructure geometry, which target the improvements in ultrasonic imaging devices that NRL will evaluate for U.S. Navy mine hunting requirements.

2. Distributed Electroceramic Composite Actuation for Active Structural Control

This program will actively seek to control the vibrations in a mechanical structure by devising, fabricating, and testing composite laminates. Researchers will incorporate electroceramic sensor and actuator components to achieve active control over the plate's vibrations.

3. Development of Fine-Scale Piezoelectric Ceramic/Polymer Composites by Fused Deposition Process

The objective of this program is to fabricate fine-scale piezoelectric composites. Researchers will use fused deposition processing methods to prepare piezoelectric ceramic green forms of appropriate spatial geometry. These green forms will be burnt-out, sintered, and then backfilled with polymer to make the desired piezocomposite structure.

4. Fine-Scale Piezoelectric Ceramic/Polymer Composites Via Fused Deposition Process

The objective of this program is to devise methods of synthesizing fine-scale piezocomposite materials in large areas at low cost. Researchers will devise methods to form piezoelectric ceramics into complex spatial forms using fused deposition processing methods, will impregnate these forms with a polymer to form a piezocomposite material, and will evaluate the electromechanical properties.

5. Multiple-Scale Micromechanics of Polycrystalline Piezoelectric Ceramics

This research initiation proposal supports a tightly coupled experimental/theoretical program in the linear and nonlinear constitutive response of piezoelectric ceramics. Emphasis will be placed on the role played by microstructural-level phenomena that occur at the grain and subgrain levels and result in a constantly evolving microstructure that then influences the overall constitutive response. Researchers will develop a thermodynamically sound constitutive model that incorporates the micromechanics as internal variables.

6. Tactile Computer Reader for Knowledge Representation

The objective of this research project is to find a combination of piezoelectric materials and surface mount electronics that, in a unique geometry, will produce a reliable Large Tactile Computer-Controlled Array suitable for a full-page Braille display. The choice of

piezoelectric materials and geometry must produce a robust design that, when mass produced, is affordable. Reliability is a key aim since a dense tactile array can have several thousand pins, all of which must work. Present displays of 40 characters compared with the proposed display of approximately 1,000 characters means that the manufacturing yield must be improved by a factor of 25. Research directed at the piezoelectric ceramic materials to identify the stress/strain, applied electric fields, and fixture cycles to predict life time requires finite element computer modeling. To enhance the manufacturability and reliability, a geometric modular approach that incorporates planar element rather than stacked cantilever actuators is required. Thus, the large array will be made from many small, flat, identical, mass-produced modules.

E. SINGLE-CRYSTAL PIEZOELECTRIC PROGRAMS

1. Workshop on Ferroelectric Single Crystals With High Electro-mechanical Coupling: Growth, Characterization, and Applications

This program focuses on:

- Identifying and optimizing materials with high electromechanical coupling
- Growing single crystals from the lead zinc niobate/lead titanate (PZN/PT) and lead magnesium niobate/lead titanate (PMN/PT) solid solutions at compositions near their morphotropic phase boundaries
- Characterizing single crystals' elastic, dielectric, and piezoelectric properties
- Optimizing the material composition to yield high electromechanical coupling
- Organizing an international workshop on the growth of single-crystal ferroelectrics.

**APPENDIX B. MEMORANDUM SUMMARIZING THE
RESULTS OF THE NOVEMBER 1996 NAVY WORKSHOP**

APPENDIX B. MEMORANDUM SUMMARIZING THE RESULTS OF THE NOVEMBER 1996 NAVY WORKSHOP

Memorandum

4 December 1996

To: RADM Paul G. Gaffney II, ONR 00
Dr. Fred E. Saalfeld, ONR 01

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Mr. Paul M. Bridenbaugh, Crystal Associates Inc
Mr. Stephen C. Butler, NUWC 2131
Dr. Robert Cantrell, NSWC 7302
Dr. Robert Corsaro, NRL 7135
Dr. Jerome DeJaco, NCCOSC 711
Dr. Wesley Hackenberger, TRS Ceramics Inc
Dr. Thomas Howarth, NRL 7135
Dr. W. Jack Hughes, ARL (Penn State)
Mr. Bruce M. Johnson, NEOD
Mr. Jan F. Lindberg, NUWC 213
Mr. Scott Littlefield, ONR 321
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Professor Thomas R. Shrout, Pennsylvania State University
Dr. Wallace A. Smith, ONR 332
Mr. Frank A. Tito, Code 2131
Dr. Carl Wu, ONR 332

Copy: Dr. Eugene A. Silva, ONR 33
Dr. Robert C. Pohanka, ONR 332

Subj: Conclusions of the Workshop on Applications of High Performance Piezoelectrics

Encl.: (1) Workshop Participants & Invitees
(2) Workshop Agenda
(3) Workshop Presentation Materials

1. This memorandum summarizes the conclusions of the workshop held on 22 November 1996 to assess the potential of high performance single-crystal piezoelectrics in Navy applications.

2. We find that the recently discovered properties of the relaxor-based ferroelectric single crystals promise revolutionary advances in performance for essentially all Navy acoustic transduction systems, both those in current fleet service and those in current development projects. The reported high strain level (exceeding 1%, compared with 0.1% in conventional piezoceramics) and high electromechanical coupling (exceeding 90%, compared with 75% in conventional piezoceramics) will lead directly to significant gains in power, bandwidth, and signal-to-noise in Navy sonar and vibration control systems. If these materials can be made, at reasonable cost, in the sizes and shapes required, and if the materials and their properties survive the demanding environmental stresses placed on them, we foresee these new piezoelectric crystals having dramatic impacts on the performance of Navy acoustic transducers.

3. We provide brief, unclassified summaries below of the potential impact of these single crystal piezoelectrics for current transduction systems in the fleet and in development. These first-blush assessments were discussed in small specialist working groups in detail and presented to all workshop participants for comment. The drafter of each paragraph is identified.

3.1 High Power Projectors The high energy density material should allow the development of high power projectors of substantially reduced weight and increased bandwidth. Large strain may allow simpler devices with reduced heating and reactive power requirements at band edges. Single crystals should result in more consistent material characteristics, beneficial in both large projectors and arrays. The technical issues for this application are: the ability to make crystals in the needed shapes, the sizes of available crystals (may need new device design approaches), the crystals' brittleness and other mechanical properties, poisson effects at interfaces in device structures, high voltage engineering (practical field limits, safety, breakdown), electroding methods (embedding) to offset high electric fields, and performance under pre-stress (depth dependence). (Rynne, NCCOSC)

3.2 Towed Arrays For use in towed arrays, the high hydrostatic response and capacitance of the piezocrystals allow a reduction in hydrophone element size. This savings in sensor volume allows the array diameter to shrink resulting in reduced array volume and less drag. The technical issue for this applications verification of high hydrostatic response. (Powers, NUWC)

3.3 Weapons Frequency Tonpilz Arrays Increased sound level and bandwidth arrays will result from the single crystals' increased strain and coupling properties. Issues are stability with time, temperature and pressure, properties under mechanical prestress, and low high-power losses. The size requirement are stacks approximately two inches long and one inch in diameter composed of 5 to 10 pieces. Electrode design and fabrication by diffusion bonding may be required. (Frank Tito, NUWC)

3.4 Sonobouys and Hull Mounted Arrays With flexural disk hydrophones and accelerometers for sonobouys and hull-mounted arrays, the coupling factor is important: higher k_p implies a higher signal-to-noise ratio. The possibility exists for crystal growth through the center electrode to fabricate a bimorph flexural disk in one operation. The technical issues for this application are: verification of high k_p and thick film crystal growth on an electrode. (Moffett, NUWC)

3.5 VLF Hydrophones The high electromechanical coupling coefficient may be exploited in a neutrally buoyant bi-laminar thin beam transducer which would provide an intrinsic dipole pattern at very low frequency. (Benjamin, NUWC)

3.6 Torpedo Guidance Sonar The single crystal properties (relative to PZT-4) of higher g and d constants will allow a tonpilz element design to have significantly higher sensitivity (about 6dB), along with being able to transmit power equivalent to present designs at lower voltage drive levels. The lower drive voltages will allow using standard leads and components (lower cost) and perhaps allow a direct drive transducer (full power at battery voltage) to be used. This eliminates the voltage step-up transformer currently used.

The single crystal piezoelectrics are a softer material (more compliant) and have a higher energy density. These parameters will allow a smaller element which can be significantly shorter and lighter. The more compliant ceramic section allows lighter masses and a shorter element for the same resonance frequency, or a lower frequency for the same length elements. (Hughes, ARL)

3.7 Standard Hydrophones The outstanding feature is the potential of stability with time (vastly reduced aging compared to PZT ceramics). Other important features are: stability with temperature, stability with pressure, high sensitivity and capabilities for lower noise, and high hydrostatic response for high frequency microprobes. These new materials could provide direct, lower noise replacement for standards which still use traditional piezo crystals. Critical issues for this application are the verification of low aging and high hydrostatic response (Powers, NUWC)

3.8 Diver-Held and UUV-Mounted Mine Imaging Sonar Diver-held and UUV-mounted mine imaging sonars for classification are currently limited to one-dimensional array based system. The next generation of imaging sonars based on 2D arrays for diver held and remote operated vehicle applications will provide an order of magnitude improvement in image quality. Thousands of single crystal elements populating a 2D array will provide an improved capability over a conventional PZT array. The promise of increased element sensitivity and higher transmitted power will increase the range at which target images can be collected. Operationally, this will mean increased coverage rates and improved survivability of personnel and equipment. (Johnson, NEOD)

3.9 Low Frequency Mine Classification Sonars The potential of single crystals offers several breakthroughs for U.S. Navy low frequency classification mine hunting. The potential is for lower frequency (because of the softer mechanical materials properties), higher transmit power (because of the high piezoelectric charge constants and high dielectric), increased bandwidth and comparable dielectric loss parameters at high field. The other attractive component of this is that with the increased acoustic performance potential of the single crystal, this performance could be utilized on several Navy platforms including AUV's, UUV's and driver held sonars. The promise is that the end use will have increased performance in terms of the low frequency and high power for both floating and bottom penetration targets. (Howarth, NRL)

3.10 Actuators and Sensors for Active Control of Machinery Platform Noise Transmission The increases in available strain and dielectric constants of single crystal piezoelectric materials appear to hold promise as force actuation in series with isolation mounts. For the active noise control system, the single crystal materials could be used to sense force transmission. To be effective, the sensor must be thin enough to be minimally invasive (i.e. not generate additional resonances at low frequencies) to force transmission and sensing. Further, the sensor must be rugged (shock and load resistant). For engineering design, a complete cataloging of piezoelectric parameter will be required. (Cantrell, NSWC)

3.11 Structural Vibration Control for Torpedo Self-Noise Reduction The high strain and broad bandwidth provided by the single crystal piezoelectrics could be utilized in a "smart" coating on the interior of the torpedo (shell) body to eliminate propulsor-produced and flow-noise produced structure-borne noise that would contaminate the self-noise thresholds of the nose-mounted sensor array. What is needed is a smart panel of very thin thickness that is capable of reacting to flexural waves greater than 2 kHz. (Lindberg, NUWC)

3.12 Active Coatings Based on the parameters currently available, if this transducer material can be manufactured at sufficiently low cost, it appears to offer significant advantages as an actuator layer in an ABC Type Smart Acoustic Tile. Specifically, its high d_{33} and available strain will permit operation at significantly lower frequencies than systems currently in development. The wide operational bandwidth of this material should reduce signal delays and contribute to more stable and robust controller operation. (Corsaro, NRL)

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13. ABSTRACT (Maximum 180 words) Piezoelectricity was first discovered by the Curie brothers in 1880. During the 1940s, piezoelectric ceramic materials were first used in commercial devices, and new materials and other applications have continued to develop over the years. Most recently, however, relaxor-based ferroelectric single crystals have been produced. In most cases, these single-crystal material properties, exceed those of conventional piezoelectric ceramics. The purpose of this study was to determine the current commercial and military uses of the piezoelectric materials, the properties that are important to these uses, and the impact of substituting single-crystal materials for the piezoelectric materials. Service and Defense agency piezoelectric development programs are discussed, as is the possibility of restructuring these programs to take advantage of the single-crystal materials. Novel military uses for single-crystal piezoelectric materials are given, and important commercial applications for single-crystal piezoelectric materials are identified. Finally, issues such as design modifications needed to produce devices using the single crystals are addressed.			
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